National Aeronautics and Space Administration Langley Research Center's Design Criteria for Small Unmanned Aerial Vehicle Development

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SMALL UAV AIRWORTHINESS DESIGN

National Aeronautics and Space Administration (NASA) Langley Research Center (LaRC) has a long, rich tradition of advanced aeronautics research using subscale aircraft. LaRC has developed detailed procedures and guidelines that set forth criteria for the design, analysis, quality assurance and documentation for wind-tunnel model systems to be tested at the LaRC. The criteria are intended to prevent model systems failure and/or facility damage. However, traditional wind tunnel experimental testing can not meet all of the aeronautics research requirements. To that end, LaRC uses free flying subscale models in large wind tunnels and small Unmanned Aerial Vehicles (UAVs) to extend traditional aeronautics research testing capability. With the absence of standardized and accepted design criteria for free flying subscale testbeds, LaRC has adapted the wind-tunnel model systems criteria to guide the development of theses free-flying vehicles and is in the process of developing unique criteria specifically for these testbeds.

This paper will review LaRC's criteria and procedures for design and development of wind tunnel test articles (models). The paper will outline how this set of criteria, along with other limited but established criteria and best practices from the user community, has been applied to the development of small UAVs, giving specific examples of recent or current activities. In addition, shortcomings of the current guidelines will be discussed and recommendations will be presented.

1.0 INTRODUCTION

NASA LaRC routinely performs wind tunnel tests using scaled research experimental test articles. These tests are performed under various conditions that subject the test article to aerodynamic forces that induce loads that could cause structural or component failure, resulting in damage to the wind tunnel facility as well as to the test article. Since these research tests may produce aerodynamic effects that are not easily predicted, guidance has been developed, Langley Procedural Requirement (LPR) 1710.15[1] (Wind Tunnel Model Systems Criteria), to aid in the prevention of test article failure and/or potential facility damage during testing.

In addition to wind tunnel aerodynamic testing techniques, Langley Research Center developed a free flight testing program that uses unpowered subscale test articles. These test articles are usually dynamically scaled and are dropped from a helicopter at altitudes in the range of 10,000 feet. They are flown utilizing a ground station and telemetry system to perform research manoeuvres and are recovered with remote deployment of an onboard parachute system. In addition to flight testing, these experimental test articles are usually tested in a

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wind tunnel system and must be designed to comply with the LPR 1710.15 document. Since it is very difficult for these subscale flight articles to meet the stringent criteria of this document, waivers are reviewed on a case by case basis for those areas where the established criteria cannot be met.

UAV systems being developed by Langley Research Center attempt to meet the criteria established in 1710.15, however, it is virtually impossible to meet both the research requirements for dynamic scaling and the document criteria. Additionally, the safety factors for the design criteria for LPR 1710.15 are considered too stringent for free flight test articles and LPR 1710.15 does not address the ground support equipment, telemetry, electronics, and avionics required for free flight test articles. To structurally certify these test articles that cannot meet the required margins of safety, proof loading is used to qualify the test articles for the anticipated flight loads.

It has become apparent an additional document is required that is tailored to subscale flight systems to provide reasonable guidelines for design and development of these systems to assure adequate safety margins and yet meet the research criteria. Since there is a not standard method in existence, this document would provide the proper guidance and documentation required to validate subscale flight systems for safe testing. The remainder of this paper will discuss these areas in more detail and is organized as follows: 2.0 Wind Tunnel Model Systems Criteria, 3.0 Dynamically Scaled UAV Design, 4.0 Small to Micro UAV Development, and 5.0 Lessons Learned and Conclusions.

2.0 WIND TUNNEL MODEL SYSTEMS CRITERIA

2.1 LPR 1710.15 Wind Tunnel Model Systems Criteria

NASA Langley Research Center has long been recognized as a world leader in performing aerodynamic testing using scaled research test articles. These tests are performed in a wide variety of facilities that produce vastly differing test conditions. To meet the test objectives and to maximize research dollars, the test articles vary greatly in the types of construction methods utilizing a wide variety of materials. The tests subject the test article to loads that can cause structural damage or failure, leading to the loss of the test article and damage to the wind tunnel facility. Since testing may produce aerodynamic and other forces that are not well understood, LaRC has developed engineering requirements (LPR 1710.15 Wind Tunnel Model Systems Criteria) to aid in the design and evaluation of test articles in order to prevent model system failure and/or facility damage.

The LPR 1710.15 is a living document in that it is periodically updated as new testing techniques, advanced materials or new fabrication techniques are developed. The LaRC Wind Tunnel Model Systems Committee is the owner of the document and meets periodically to address additions, deletions, and changes to the document. The most recent revision is from July, 2004 and is scheduled to expire in July, 2008. Examples of recent changes include a detailed section on fracture mechanics analysis and the inclusion of drop models and remotely piloted vehicles.

LPR 1710.15 sets forth procedures and guidelines for the design, analysis, quality assurance, and documentation for wind tunnel test articles to be tested at LaRC. A major emphasis is given to analysis to ensure the structural integrity of the model system. The factors of safety that are required are tailored to the complexity of the analysis. A very conservative handbook analysis will require a substantially higher factor of safety than a detailed Finite Element Analysis. The guidelines are written to give significant latitude to the model designer to tailor the complexity of the analysis as necessary to verify model integrity. The

requirements of the document are mandatory for the major facilities where model failure may produce significant facility damage and/or loss of the test article represents a significant financial loss. It is used as a "best practices" guide in non-critical facilities where aerodynamic loads tend to be lower and risk to the facility is slight, but the criteria can be relaxed significantly, particularly in the areas of documentation and quality assurance.

LPR 1710.15 defines the responsibilities of the Facility Safety Head, Model Safety Engineer, Research Project Engineer, Technical Project Engineer, and Test Engineer. Model system reviews are held as deemed necessary. Any of the parties listed above can call for a formal design review if the model is especially complicated, potentially hazardous to LaRC facilities, or requires a number of deviations from the guideline. A formal procedure for requesting deviations from LPR 1710.15 is given in the handbook. Unless specifically noted, applicable provisions of a number of referenced standards, codes, and handbooks are acceptable. Examples of these are ANSI, ASME, ASTM, SAE, and certain DoD handbooks.

2.2 Free Flight Models

There are two classes of research test articles that fall outside the normal range of testing. These are Free Flight models and Drop models. Both types of models are dynamically scaled (discussed in section 3.1); defined as the geometry, mass, and inertia being scaled to match the target aircraft. With respect to the model geometric scale factor, spatial dimensions are scaled linearly, mass is scaled to the 3rd power and inertia is scaled to the 5th power. Free Flight models will be addressed first. These are dynamically scaled models which are flown in a large, low speed wind tunnel using pneumatic powered ejectors for thrust. They are tethered by an umbilical cord which provides the air and electrical signals for actuation and other instrumentation. When free flying, the umbilical is loose, providing minimal interference. These models are also statically tested on a traditional sting mount. These types of models have long been included within LPR 1710.15. Historically, the aircraft configurations tested were military fighter class vehicles. Since these were large scale models (~15% scale) of dense target aircraft, achieving dynamic scaling was not difficult using substantial internal structure to meet the required safety factors. Recently, a Free Flight model, shown in Figure 1, was built for the conceptual Blended Wing Body transport aircraft. Due to the much smaller scale (5%) and lower density of the target vehicle, dynamic scaling was difficult. Thin, stressed skin composite structure was used for the entire structure. Due to the nature of the testing, aerodynamic loads were not necessarily the limiting design load. The model was built to have breakaway features in the event of impact with tunnel structure or model umbilical. This was to minimize the repair cost of thin composite structure and drive fracture points into more easily repaired structure. By design, these components did not meet the safety factors of LPR 1710.15. The criteria were met where feasible, and in other cases, the non-compliant items were identified and the appropriate deviations acquired.

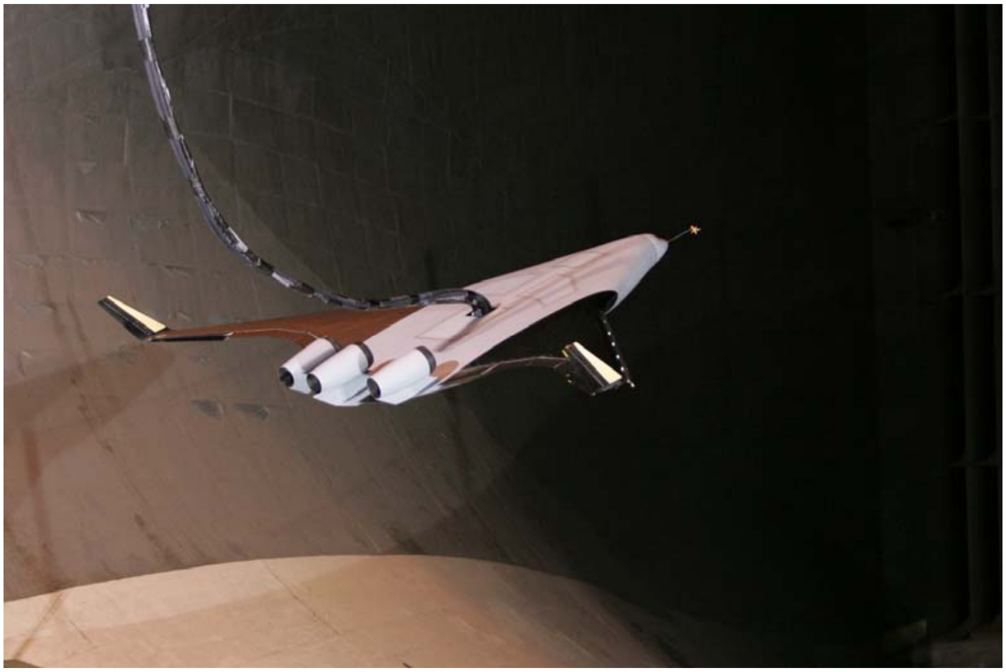

Figure 1: BWB Free Flight Model

2.3 Drop Models

Drop models have recently been added to the scope of LPR 1710.15. These models are much heavier than Free Flight models and are considerably larger scale. They have traditionally been dropped from a helicopter at an altitude of about 10,000 ft, and recovered via parachute deployment on a remote land based site or on water. The most recent Drop Model was a large F-18[2] (22%) that weighed ~900lbs and is shown in Figure 2 below along with an X-31[3] Drop Model. The F-18 model was also statically tested in a wind tunnel using a traditional sting mount. Meeting the required safety factors for aerodynamic loading is normally not a challenge. Add-ons such as high lift devices and stores are vulnerable to landing damage and are often designed to break away under low impact. The drop testing also requires the model to survive unanticipated events such as awkward landings, and parachute deployment shock. These events have to be anticipated and designed appropriately to survive intact or to fail in a predictable and easily reparable manner. LPR 1710.15 does not address this scenario. Deviations are usually required so that the research requirements can be met while managing the trade-off between sturdiness of design and repairability in order to perform multiple drop tests.

Figure 2: F-18 (l) and X-31 (r) Drop Models just after release from helicopter

3.0 DYNAMICALLY SCALED UAV DESIGN

3.1 Dynamic Scaling

In order for a subscale body to appropriately represent the motion and response of a full scale body (or aircraft in this case), the test vehicle is required to be dynamically scaled[4,5]. This means that not only is the test vehicle scaled dimensionally, but also in weight, inertias, control, and actuation systems. For most wind tunnel testing, the scaling requirement is dimensional only. However, to fully exploit the dynamic environment of free flight testing requires dynamic scaling of a subscale vehicle. The challenge to airframe design, fabrication, and outfitting presented by the dynamic scaling requirement can push the limits of the designers and the state-of-the-art in system components. As the scaling factor, K, decreases, the airframe dimensions decrease proportionally, the weight by a factor of K^3, and the inertias by a factor of K^5. However the data acquisition and control systems (including actuators and propulsion systems) must **increase** in speed by a factor of $1/\sqrt{K}$. For a 5.5% dynamically scaled model, this equates to a response time increase of ~ 4.25%. It should be noted here that this type of scaling assumes rigid body dynamics and is not aeroelastic scaling. Figure 3 below shows Langley's 5.5% dynamically scaled transport vehicle[6] with the full scale vehicle in the background. Also shown is a comparison of the two vehicles.

	Length	Wingspan	Weight	Roll inertia	Altitude	Airspeed
Full scale 757	44.3 m	37.8 m	90718 kg	$2.64e^6$ kg-m^2	3962 m	515 kmph
5.5% d.s. model	2.44 m	2.08 m	22.5 kg	1.8 kg-m^2	305 m	120 kmph

Figure 3: Dynamically Scaled Test Vehicle

3.2 Dynamically Scaled Design

Airframe design of a dynamically scaled vehicle begins by approximating the outer mold lines (OML) of the airplane or by using the manufacturer's data to develop a surface model of the intended aircraft. Once the OML has been defined, a weight and inertia study is needed to obtain the final scale of the vehicle. This study should be performed using computer solid model software for the greatest accuracy as this design effort is an iterative process between the engineering team and the fabrication team to obtain an accurately dynamically scaled model. This study using solid model generation is the most important engineering operation of designing a dynamically scaled model. Without this study, the final fabricated vehicle could be overweight, under powered or inherently weak and fragile structurally. The weight and inertial study must include all aspects of the anticipated model design such as structural (interior and exterior), control surface systems (servos, linkages), sub-system components (landing gear, steering, braking), power systems (batteries, wiring), avionics, control and data systems (electronics, shielding) and the power plant. The most important governing factors for the design study are the control surface actuators and the vehicle's power plant(s). To be cost effective in the design, these items should be commercial off the shelf (COTS) or the project risks high development and testing costs and a lengthy schedule associated with the validation of these units. These items will, for the most part, determine the final scale of the vehicle and its final vehicular performance. A similar approach should also be use for all other subsystems in the mechanical and the electrical/electronics design.

As for the OML and some interior structure, composites (Fiberglass and/or carbon fiber) can be used as a starting point for this study since their densities and strengths are easily evaluated. Composites also offer a high strength to weight ratio needed to keep the final model weight manageable and still strong enough to handle appropriate g loadings, which should be used as a minimal g rating of the final design. If weight (and therefore airframe structure) is an issue, then it is imperative that reasonable g value be identified from the airplanes flight envelope. This estimate, along with the factor-of-safety and airspeed (dynamic pressure), will guide the design of the main structural components in the airframe. Light metals (aluminums) can be used for high load carrying locations (wing spars, landing gear attachment, etc.). As a general rule, the dynamic scaling of a fighter type jet is more forgiving than the dynamic scaling of a passenger airliner, due to the fact that jet fighters are denser than passenger jets. Therefore jet fighter models can use more weight within their primary load carrying structures and hence obtain a higher g-load rating. It should be noted that dynamic scaling is a 5th order power while volume and weight are a 3rd order power, so the inertias of the design could outpace the weight growth exponentially if left unchecked. Hence an accurate engineering design study is required to keep the vehicle within the inertial values required at a specific scale and satisfy that a

dynamically scaled solution is believable. Figure 4 shows a computer designed, dynamically scaled research model.

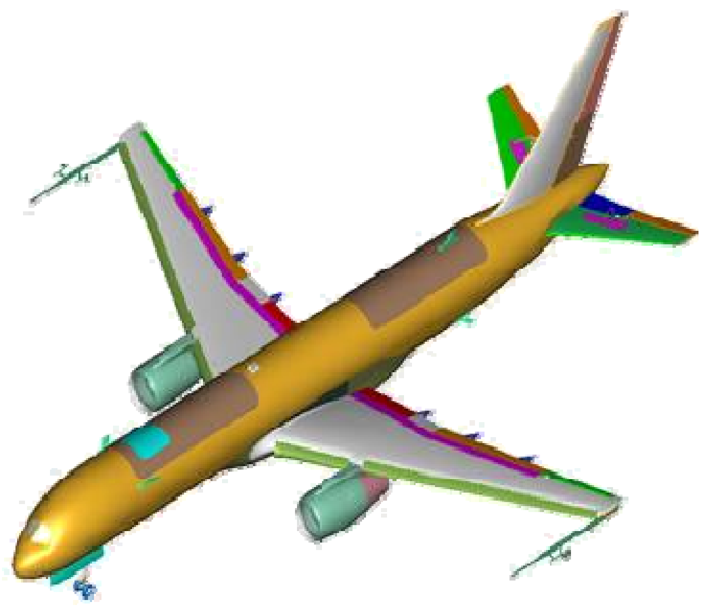

Figure 4: 5.5% Dynamically Scaled Solid Model

Once an appropriate design scale has been determined, then this design study can be converted to the final design solution. This final design should include all aspects of the model which includes all nuts and bolts, hinges, adhesives, sub-systems components, pneumatic lines and the primer/paint needed to finish the model. Hence an iterative process between the engineering and the fabrication departments is needed to ensure an accurate computer solid model that aligns itself with the final vehicle components as the parts are being fabricated and installed. As the fabrication progresses, the engineering department can, on a daily basis, monitor the inertias of the final assembly of the vehicle and make adjustments (redesigns) accordingly. During the NACA era of NASA this was done via hand calculations which required significant resources for an accurate and believable solution. Once the model nears final completion, dead weight proof-loading (lead or steel bags) can be used to back up the engineering analysis and ensure an acceptable design. After the internal outfitting, the model can be tested for its inertial values. The easiest and most accurate method used is the tri-filar or bi-filar pendulum swing test located inside a vacuum chamber or a chamber of helium. However, due to the size of the model this approach may not be cost effective. Leveraging off of the past NACA era[7,8], an air damping model can be fabricated and utilized to take into account air damping on light weight models (less than 250 lbs.). The air damping model needs only to approximate the vehicles plan-form, side-form, and front-form geometries. It can be made from any light available material such as residential house insulation or balsa and paper. The three inertias (roll, pitch, and yaw) from this air damping model are used in the final calculation of the vehicles inertias. The final computed values can then be compared to the computer solid model values and a percent error can be calculated. Figure 5 shows the dynamically scaled model undergoing inertial testing.

Figure 5: Inertial Testing of a Dynamically Scaled Model

Validation of the design and fabrication of the model to required standards can be accomplished via two basic methods, each with distinct advantages. One is analysis, the other is through testing. A structural analysis, whether done by hand for simple structures, or by computer for more elaborate designs, can verify that the model will withstand the loading and stresses that are estimated for a given flight envelope. However, analysis itself will not reveal flaws or irregularities in the as-built airframe and many assumptions must be made. Testing, be it sample, subsystem, or system level testing, provides insight into the design as it is fabricated. This testing may take the form of destructive testing (test until failure), non-destructive testing (x-ray or ultrasonic techniques) or proof loading. Other factors to consider when testing a structure are static vs. dynamic loading, fatigue, and environmental effects (temperature, pressure, moisture, humidity, etc.). Whatever method is chosen to validate the design and fabrication of an airframe, it is important to realize the assumptions that were taken and the limits of the data that is provided.

3.3 Actuation, Payload, Powerplant, and Electronics Design Issues

As mentioned previously, the dynamic scaling requirement applies not only to the airframe, but also to the control, actuation, and propulsion systems. This increase in response time (for a *sub*scale vehicle) places greater demands on certain subsystems than might arise if these same subsystems were designed or chosen based solely on airworthiness criteria. This in turn can restrict or even eliminate the use of COTS components for these systems, increasing the time and cost of UAV development.

Subsystem and component weight and location play important roles in being able to meet the dynamic scaling requirements, which are derived from the full size flight vehicle and the scaling factor. While the as-built weight of the aircraft can easily be tracked with a spreadsheet as various components are added and the airframe assembled, the inertia scaling is more complicated, especially for spatially distributed components. Inertial tracking necessitates the need for a solid model of the aircraft and all components, with corresponding size and weight properties defined. However, inertia is not the only criteria for determining the location of components within the airframe. Other aspects to consider include EMI and RFI concerns, center-of-gravity (cg) location, antenna placement for optimal transmission and reception, shielding, available structure for mounting, temperature sensitivity, and space availability, especially on small UAVs. The need to optimize these criteria along with meeting a specific inertia target drives the designer to utilize solid modelling for weight and inertia estimating as the design progresses.

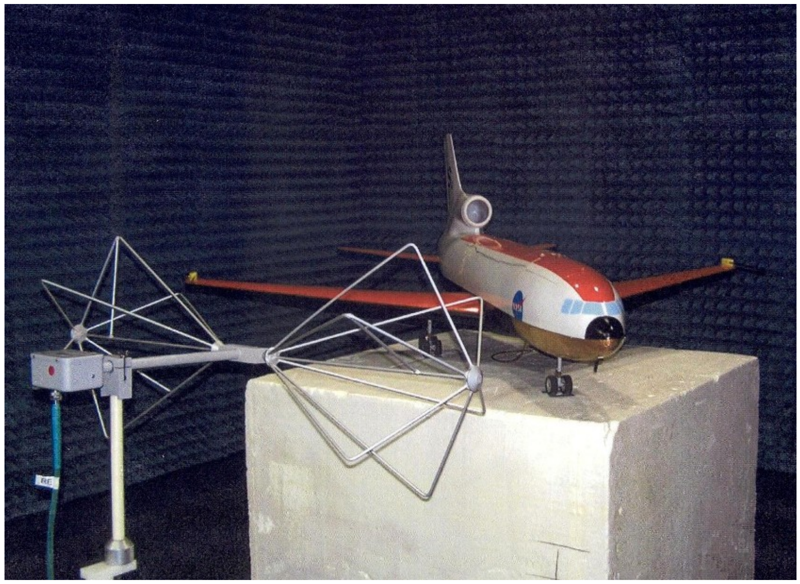

Figure 6: Subscale Model in Anechoic Chamber

As an airframe gets smaller, the available room for spatially separating components to minimize electrical interference is reduced and the greater the attention that must be paid to proper shielding and grounding techniques. And because many small UAVs are heavily laden with electronic payloads, the need for proper electromagnetic interference (EMI) and radio frequency interference (RFI) testing, identification, and reduction plays an important role in the airworthiness of the airframe. Usually, prefabrication design can only address higher level EMI issues. In the end, much of the EMI mitigation involves system level testing and evaluation. LaRC has made extensive use of an anechoic chamber to identify potential interference issues and to develop appropriate shielding and grounding designs. Figure 6 above shows a turbine powered UAV transport model in the chamber for testing.

The anechoic chamber testing described above characterizes the model's radiation as a black box; it quantifies the emissions of the model from an outside perspective. To get further insight into the interaction of the different electrical components inside the airframe, more invasive techniques must be employed, such as investigating individual control or signal lines and looking for specific sources of noise and grounding problems. High frequency digital electronics are a frequent source of noise that may contaminate adjacent or insufficiently isolated analog lines. Whenever a change is made to the electrical system, whether it is an addition or simply a relocation of existing components, it is essential that proper electrical system functionality be verified before flight testing.

4.0 DESIGN CRITERIA FOR SMALL AND MICRO UAS

4.1 Introduction

Small Unmanned Aerial Systems (UAS) present a particularly interesting capability to conduct a number of scientific, commercial, and military functions in a particularly cost effective manner. There is a large variation in the types and capabilities of these systems, even within the confines of a "small" air vehicle system. What is ill-defined about all of these systems is what criteria were used in the design of these systems. Clearly, for acceptance into the larger class of air vehicle utility, such as being able to use the National Airspace System

(NAS), such criteria will need to be established and documented. This section describes work being done at NASA Langley Research Center to help identify a common design criteria for small UAS.

4.2 Approach

Typically, there are two general approaches to the development of design criteria for air vehicles and their systems. First, there is a comprehensive approach which seeks to provide a detailed "how-to" for every aspect of the design of the vehicle and required systems. Examples of this include FAR Part 23[9] and 25[10]. The philosophy is to follow all of these rules to develop an airworthy vehicle. Pre-flight analysis and testing is done to ensure compliance with the rules. The drawback to such a comprehensive approach is that it tends to focus on legacy configurations and limited mission types in its rules. Unconventional vehicles, unique missions, or even the use of newer technologies can cause the use of these "legacy" standards to be problematic. The alternative approach is to develop a "minimalist" set of criteria that, if followed, would increase the likelihood of developing an airworthy vehicle. Pre-flight analysis and testing would be limited to that which is strictly necessary to ensure safety of flight during the flight testing.

Along with specific design criteria, there are often policy considerations which help define necessary design criteria. In the case of the US DoD, there is a set of "Safety Precepts" which define specific design characteristics which have been decided, by policy, should be used in the design and operation of a UAS[11].

In addition to identifying the required design criteria for small UAS, consideration should be given to size and mission. Clearly, a slow, hand launched sub- 0.5kg (1 lb) air vehicle represents a different level of hazard than a 90kg (200lb) air vehicle. For this reason, a three-tiered approach is taken for categorizing the small platforms on the basis of size and speed: (a) Mini-UAV where the air vehicle weighs less than 5kg (11lb) and whose maximum speed in level flight is less than 139 km/hr (75kts); (b) Very Small UAV where the air vehicle weighs less than 25kg (55lb) and whose maximum speed is less than 278 km/hr (150kts); (c) Small UAV where the UAV weighs less than 100kg (220lb) and whose maximum speed in level flight is less than 463 km/hr (250kts). Specific examples of each of these design criteria for the different vehicle sizes are given in the following paragraphs.

4.3 Design Criteria

For the smallest UAVs, the "Mini UAV", the design criteria is straightforward. Typically, unmanned aerial vehicles of this class, such as those shown in Figure 7, are designed with small size and low weight as their overriding features. As such, tradeoffs in durability, subsystem redundancy, etc. are frequently made. However, efforts should be made during the design and fabrication process to consider safety in normal operation as well as potential crash scenarios. The safety of personnel during operations (launch, flight, recovery, and failure) should be considered as the overriding criteria should a tradeoff in design be required. The design criteria fall into three basic categories: (a) design constraints or requirements, (b) design features or required equipment and (c) pre-first flight validation tests and documentation.

Figure 7: "Mini-UAV" measures < 15 inches (38cm) square

Examples of the first type of design criteria include a G-loading constraint that the vehicle must be designed for a +3g/-1g flight load at the maximum gross weight. This type of design constraint comes from reviewing data from operational experience with instrumented aircraft of this class to determine the loads most commonly measured in flight, particularly during remote-controlled flight where there is no immediate feedback to the pilot of G-loading resulting from commanded input. Others include a stall speed (which, in some cases, may be empirically derived by determining the ability of a group of subjects to hand launch a vehicle of a given weight), landing sink speed, and others.

The second type of criteria involves required features or required equipment. This would include the requirement that the vehicle have sufficient control to return to level flight at any point in the flight manoeuvre envelope up to and including stall. Other examples include a 'failsafe' system which prevents flyaways and/or provides a return-to-base capability in the even of loss of command link, an easy to reach external 'kill switch' that disables the motor and/or battery power, and others.

The third type of criteria involves verification that the vehicle meets its intended mission and the previously mentioned criteria as well as documentation on how the system is to be operated and maintained. These pre-first-flight tests include structural load tests up to the design G-loading, ground range tests for all command links, ground verification of failsafe and kill-switch functions, drop tests to verify landing sink rate durability, and others. Documentation should include what procedure to use pre-flight to ensure the vehicle is safe to operate, operating instructions, emergency procedures, and inspection/maintenance procedures and intervals.

For the "Very Small UAV" (Figure 8.), this category of vehicle represents an outgrowth of the typical model aircraft type vehicle that is limited to 25kg (55lbs) but with a significant improvement in the overall acuity of the design criteria used to develop the system. Additional criteria beyond the previous class include higher stall speeds and g-loadings, higher landing sink rates, more control authority and/or control volume constraints, manual reversion modes for autonavigation systems, and others. Additional pre-flight testing would include operation of control surfaces with maximum structural load weights imposed to verify correct operation, longer command link range ground verification testing, simulation of flying qualities pre-flight, and others.

Figure 8: "Very Small UAV" weighing approximately 15 lbs.

For the largest class, the "Small UAV", there represents a significantly larger potential hazard. As such, additional precautions must be taken in the design and pre-flight testing. Some of these include: roll and pitch rate authority constraints, primary control surface (aileron, elevator) redundant servo actuators, control horns and redundant signal paths to the servo actuators, redundant receivers and an isolated manual reversion mode for systems with auto-navigation units. Failure or shutdown of the primary engine should not disable the primary flight controls, including and radio receiver, auto-navigation unit, servos, etc. Redundant power sources must be included to power the servo actuators, radio receivers, command/control links, and auto-navigation unit. The vehicle should be designed to endure a ± 7.6 m/s (25 ft/s) vertical gust throughout the normal flight envelope. In addition, more preflight testing and verification is required for this class than previous classes.

4.4 Comparison to Other Criteria

It is sometimes useful to compare proposed criteria to other standards to identify the differences, potential strengths, and weaknesses. In the case of these categories of small air vehicles, the standards which most closely align with these design guidelines include the FAR Part 23, the ASTM Light Sport Aircraft criteria (F 2245)[12], the ASTM Mini-UAV Airworthiness (Working Draft WK5673)[13], and the RTCA SC-203 Draft UAS documents. A summary comparing elements of the NASA internal design guidelines with those found in these documents is shown below in Table 1.

				ASTM Draft	Light Sport
	Mini-UAV	Very Small UAV	Small UAV	Mini-UAV	Aircraft
Design Criteria Element	0-11lb.	11-55lb.	55-220lb.	< 55lb.	< 1320lb.
Stall Speed	Variable but < 30fps	30kts	40kts	NR	45kts
Landing Sink Speed	5fps	7fps	10fps	NR	10fps
G-loading	min +3/-1	min +4/-1	min +4/-1	Max +3/-1	Max +4/-2
Tail Volume coefficient	NR	Cvt>=0.02, Cht>=0.4 for conventional configurations	Cvt>=0.02, Cht>=0.4 for conventional configurations	NR	By Analysis
Flutter	NR	Test or Best Practice	AEER45 or test	Test/Analyze to set operating limit	AEER45 or test
Gust Load	NR	+/-20fps	+/-25fps	Must be identified, if any	+/-50 fps @ Vc, +/-25fps @ Vd
Roll Rate/Time Reqm't	NR	NR	<3s +/-30deg	Limit of 60deg. Bank	<4s +/-30deg
Factor of Safety	1	1.25	1.25 (higher for certain parts)	1.5	1.5 (higher for certain parts)
Vmax in level flight	<75kts	<150kts	<200kts, Vne < 250kts.	NR	120kts
Stability and Control	NR	Stable & Controllable, controllable in manual reversion	Stable & Controllable in either manual or auto	Positive static stability, damped oscillations	Stable & Controllable
Control Surface Deflection/G limit	NR	manual or programmed in autonav	automatic/limited or programmed in autonav	NR	N/A
Brakes	NR	reqd if Vapp > 60fps	required for runway landing	NR	NR
Pre-Flight Test Requirement					
Flight Load Test	Req'd	Req'd	Req'd	NR	Req'd
Limit Load Test	NR	Req'd	Req'd	NR	Req'd
Drop Test	6 in. vertical	14 in. Vertical	28 in. vertical	NR	Req'd
Failsafe	Req'd	Req'd	Redundant	NR	N/A
Redundant controls	NR	servos/controls	servos, receiver, power, control (i.e. auto with manual reversion)	NR	NR
Wind Tunnel Test	NR	NR	Req'd	NR	NR
Stress Analysis	NR	Key Components	Primary Structure, Key Components	NR	NR
Simulation	NR	Req'd	Req'd	NR	NR
Command/Control link range	NR	1/5 range	1/3 range	NR	N/A
Documentation Requirement					
Design Data	Req'd	Req'd	Req'd	Req'd	Req'd for certification only
Test Data	Req'd	Req'd	Req'd for Flight Safety Release only	NR	Req'd for certification only
Procedures	Req'd	Req'd	Req'd	Req'd	Req'd
Flight/Maintenance Log	Req'd	Req'd	Req'd	Req'd	Req'd
N/A = Not Applicable					
NR = No Requirement					

Table 1: Comparison of UAV Airworthiness Guidelines

5.0 LESSONS LEARNED AND CONCLUSIONS

In general, regulatory and certification processes have not been able to keep up with the accelerated pace of technology and the development of small UASs. What has developed is a mix of working standards and guidelines that overlap but yet have not been totally adopted by the appropriate governing bodies. Because UAVs by definition decouple the loss of a pilot and crew from the loss of the airframe, manned standards, which have a long history and are well established, can only provide a framework for developing UAS standards. UASs bring unique challenges to the development of airworthiness standards such as autonomy, size, maintainability, operational procedures, pilot interface requirements, and life cycle expectations.

NASA LaRC has developed several small UASs, mainly for the purpose of providing testbeds for research. They have leveraged existing documentation both from within and outside of NASA and the government to develop airworthiness guidelines for their specific operational envelope.

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